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Exergy cost analysis of a micro-trigeneration system based on the structural theory of thermoeconomics

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ABSTRACT

In this paper, an exergy cost analysis method based on the structural theory of thermoeconomics is applied to a gas-fired micro-trigeneration system, which uses a small-scale generator set driven by a gas engine and a new small-scale adsorption chiller (ADC). The thermoeconomic model for the system based on the fuel–product concept is defined to quantify the productive interaction between various components. The distribution of the resources and costs of all flows in the productive structure are calculated by solving a set of equations according to the experimental data. By adopting the exergy cost analysis method, the production performance of components at design and variable conditions of combined cooling and power are evaluated in detail. Moreover, a comparison between the method of conventional exergy analysis and exergy cost analysis is presented. The results not only reflect that the structural theory is a powerful and effective tool for performance evaluation of complex system, but also prove that the micro-trigeneration system is efficient in utilizing the low-grade waste heat.

1. Introduction

The successive energy crises have stimulated the study of more efficient ways for the comprehensive utilization of the available energy in fuels. Trigeneration—also called combined cooling, heating and power (CCHP)—is the simultaneous conversion a single primary fuel into mechanical power (electricity), cooling and heating to satisfy the consumption needs. It typically produces electricity through a reciprocating engine or gas turbine and recovers the waste heat energy remained in the exhaust gas and the coolant water, the heat gained can be made available for cooling and heating applications utilizing thermally activated technologies such as absorption chillers and adsorption chillers (ADCs). Trigeneration is generally considered as energy-saving, economic, reliable and environmentally benign.

The performance analysis of trigeneration systems is extremely important to China considering that China is just in the process of adjusting the energy structure and improving the energy utilization efficiency. Some scholars have made researches on the experimental study of trigeneration system. Most investigations are based on energy analysis [1–3] and exergy analysis [4,5]. However, the two analysis methods, although useful, have been proved not to be enough. For example, what is the exact cost of the different quality of energy outputs and how does energy degrade in trigeneration systems? Which parts of the degradation are most important, and how can designs and operations be improved to reduce resource consumption? Thermoeconomics can provide answers to these questions.

Thermoeconomics, originated by Tribus and Evans [6], combines the second law of thermodynamics with economics by applying the concept of cost to exergy, in order to achieve a better production management with a more cost-effective operation. Exergy is the most adequate thermodynamic property to associate with cost since it contains information from the second law of thermodynamics and accounts for energy quality. In the subsequent period of time, the main and more general thermoeconomic methodologies developed include the exergetic cost theory of Lozano and Valero [7], the last in first out method of Lazzaretto and Tsatsaronis [8], the average cost method of Bejan et al. [9], the specific exergy costing method of Tsatsaronis and Pisa [10], the thermoeconomic functional method of Frangopoulos [11,12] and the engineering functional analysis of Spakovsky and Evans [13]. To a certain extent, multiple methodologies with different theories and nomenclatures cause confusion and impede the development of thermoeconomics. Based on the achievements of predecessors, Valero et al. [14] developed the structural theory of thermoeconomics, which provides a general mathematical formulation using a linear model and encompasses all the thermoeconomic methodologies developed up to now, and is considered as standard formalism of thermoeconomics [15,16].

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Nomenclature

ADC	adsorption chiller
CCHP	combined cooling, heating and power
COP	coefficient of performance
CYL	cylinder
EHE	exhaust heat exchanger
GEN	generator
HWHE	heating water heat exchanger
JAC	jacket
LPG	liquefied petroleum gas
c_p	specific heat capacity (kJ/(kg K))
e	specific exergy (kJ/kg)
$\bar{e}$	molar exergy (kJ/kmol)
E	exergy (kW)
F	fuel exergy (kW)
g	characteristic function
k, k_W	unit exergy consumption (kW/kW)
$\bar{k}^*$	unit average exergy cost (kW/kW)
k^*	unit marginal exergy cost (kW/kW)
m	mass flow rate (kg/s)
p	pressure (MPa)
P	product exergy (kW)
Q	heat transfer rate (kW)
r	junction or exergy ratio
$\bar{R}$	universal gas constant
T	temperature (K)
W	mechanical or electrical power (kW)
x	mole fraction

Greek letters

κ	unit marginal exergy consumption
ξ	revised coefficient of temperature (J/(mol K))
ε	exergy efficiency
ε_{er}	reference generation exergy efficiency

Superscripts

$*$	exergy cost
CH	chemical exergy

Subscripts

0	environment
c	cooling
ce	conventional exergy analysis
e	electricity
ec	exergy cost analysis
F	related to fuel
h	heating
i, j	index for number of components
in	input
k	mixture component
P	related to product
t	total
w	related to work

It would be specially mentioned, in the same era two research methods which are easily to be confused with the structural theory of thermoeconomics appeared: Wang [17] proposed "structural" thermodynamics approach to decouple the structure of a thermodynamic process set with its working medium, and introduce optimization to the thermodynamic reasoning; Bejan [18] put forward "constructal" theory, which tries to deduce the optimal-access between volume to point or point to volume flow problems by optimizing volume shape at every length scale, in a hierarchical geometric flow structure that begins with the smallest elemental system, and proceeds toward larger constructs. These two methodologies are different from the structural theory of thermoeconomics in nature. The nomenclature "structure" in structural theory of thermoeconomics means productive structure, which attributes well-defined functional relationship for each exergy flow entering or leaving the subsystems in terms of fuel and product.

Thermoeconomic analysis distinguishes between exergy costs and exergoeconomic costs. The exergy cost of an energy flow represents the units of external resources exergy used to produce it. The exergoeconomic cost is defined as the amount of money consumed to generate an energy flow. Several authors have applied the structural theory of thermoeconomics to performance analysis of complex energy systems: combined cycle power plants [15], conventional coal fired power plants [19] and multi-stage flash desalination plants [20]. But all the prime movers in these plants are gas turbines or steam turbines; no work adopting this general theory has been published on performance analysis of energy systems driven by internal combustion engines. In the case of an internal combustion engine, work, flue gases and heat (water) are not produced separately and all of them come from the same device, they are very much connected and very much interdependent.

In order to evaluate the performance of a micro-trigeneration system which is mainly composed of a gas engine and an ADC, the exergy cost analysis method based on the structural theory of thermoeconomics is presented in this paper. The thermoeconomic models of the units of the system are defined properly; the interactive relationships among components of the system and the causality chains processes of product formation have been quantified. After solving the characteristic equations, the unit exergy costs of all components are obtained. The production performance of each component at design and variable conditions is analyzed in detail, and then a comparison between the method of conventional exergy analysis and exergy cost analysis is performed.

2. The micro-trigeneration system

The schematic diagram of the micro-trigeneration system which is developed by the Institute of Refrigeration and Cryogenics of Shanghai Jiao Tong University [3] is depicted in Fig. 1. The system can supply 12 kW electricity power and has a cooling capacity of 9 kW or heating capacity of 28 kW. It is composed of an internal combustion gas engine, a novel ADC, heat exchangers, a cooling tower, pumps, etc. The engine is a double-cylinder, four-stroke, water-cooled, liquefied petroleum gas (LPG) or natural gas fired engine. For the generator set at rated power of 12 kW, its generating efficiency is 21.4% and the temperature of exhausted gas is 580 °C. The refrigeration coefficient of performance (COP) of the ADC reaches 0.3–0.4 for 13 °C evaporation temperature with a heat source of 60–95 °C water [21]. The working pair is silica gel–water in which water is used as the refrigerant.

The engine jacket cooling water passes through the exhaust heat exchanger (EHE) and is reheated by the exhaust gas, and then passes through an ADC to produce chilled water in summer, or, passes a heat exchanger (heating water heat exchanger, HWHE) to